Geoacoustic Inversion Using Vertical Line Array Data

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LONG-TERM GOAL

The long-term goal of this work is to develop a method for inverting for the acoustic parameters of the ocean and ocean bottom using acoustic data measured on a vertical line array. Funding from this grant was also used to improve, maintain, and distribute a state-of-the-art acoustic normal mode model and to publish the results of previous work performed under ONR funding.

OBJECTIVES

The objectives of the FY99 work were to finish developing the software needed to perform the mode extraction and geoacoustic inversion, to conduct simulation studies of how the method is expected to work on real data, and to evaluate the practicality of the method by applying it to measured data.

APPROACH

The technical approach for the geoacoustic inversion method being investigated is (1) to use measured data on a vertical line array (VLA) to extract the depth-dependent mode functions of the environment, and (2) to invert for the environmental parameters by using a non-linear least squares technique for finding the best match between extracted and modeled mode functions. The approach for evaluating the usefulness of the method is to apply the method to the ACT II data measured in the Hudson Canyon area. This work is being carried out by Tracianne Neilsen as her Ph.D. dissertation topic in the Physics Department at the University of Texas at Austin, under the supervision of Evan Westwood. A more detailed description of the technical approach is given below.

The required experimental set-up for the mode extraction method consists of a source of opportunity moving in the vicinity of a VLA. The time-dependent, single-frequency pressure field measured on the VLA may be viewed as a matrix of pressures versus receiver depth and source-receiver range. A singular value decomposition (SVD) is performed on the pressure matrix. Under certain conditions, it may be shown, using the standard normal mode expression for the pressure field, that the resulting eigenvectors correspond to the depth-dependent normal mode functions of the waveguide. We refer to this procedure as mode extraction.

The experimental requirements for the mode extraction to work well are that the water column must be sampled sufficiently well by the receivers of the VLA and that the source must cover a sufficiently large range extent. These requirements allow the pressure matrix to be written as the product of three matrices that have the same properties as the matrices returned by the SVD. The first matrix has

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orthonormal columns, which, if the extraction is successful, contain the depth-dependent mode functions. Modes that penetrate significantly into the bottom are not well sampled at the VLA, but this is not usually a problem in the far field because those modes suffer a larger amount of attenuation and are not strong enough to affect the extraction.

The elements of the third matrix of the SVD are proportional to $\exp(ik_n r_j)/\sqrt{r_j}$. To make these rows orthonormal, a range normalization is performed to remove the effects of geometric spreading. The remaining rows will be orthonormal if the elements of the sum over range of $\exp[i(k_n - k_m)r_j]$ fill out a circle in the complex plane. The number of rotations the elements of this sum make in the complex plane is $N_{\mathrm{rot}} = (k_n - k_m)(R_{\max} - R_{\min}) / 2\pi$. The circle is most likely to be filled in if the number of rotations is large, or, equivalently, if the range extent $R_{\max} - R_{\min}$ is large.

Finally, the second matrix returned from the SVD is a real, diagonal matrix, whose elements are ordered from largest to smallest. The diagonal elements of this matrix are proportional to the modal source excitations. Thus the source depth chiefly determines the order in which the normal modes will be extracted. The main concern with the singular values is that when neighboring singular values are nearly equal, their corresponding singular vectors are not unique. In this case, the correct mode functions are linear combinations of the eigenvectors, which preserve the orthonormality condition. Modes having close singular values must be ignored in the inversion.

Once the mode functions have been extracted from the data, they may be used to invert for the parameters of the acoustic waveguide. The inversion method we used is based on Levenberg-Marquardt nonlinear optimization. In this method, the environmental parameters are adjusted to minimize the squared difference between the extracted mode functions and the corresponding mode functions modeled by the ORCA normal mode model.[1] Multiple frequencies are used in order to increase the amount of information contained in the inversion.

WORK COMPLETED

Software that performs the mode extraction and geoacoustic inversion was developed, and the entire procedure was tested using data simulated using the ORCA normal mode model and data measured during the ACT II experiment. Results have been presented to the underwater acoustics community at three Acoustic Society of America meetings.[2,3,4]

RESULTS

Simulated data were generated to investigate the conditions under which the inversion may be expected to be successful. When the two orthonormality conditions, large range extent and good depth sampling, are satisfied, the mode extraction performs well. Further studies were performed to examine more realistic experimental conditions. It was found that:

- Random source phase has no ill effects on the mode extraction. This demonstrates that the method does not require controlled sources and that ships of opportunity can be used as sources.
- An SNR of at least 10 - 15 dB is needed to obtain consistently good mode extractions. Lower SNR tends to decrease the singular values, thus increasing the probability that the singular vectors will not be uniquely determined, as described above.
- When the array is tilted, the mode extraction process can tolerate a reasonable amount of tilt. Similar to other methods, the element locations need to be known to within $\lambda/10$ for good mode

extractions. A larger amount of tilt leads to the modes being flattened out. The higher frequencies are naturally most sensitive to array tilt.

The mode extraction technique was applied to data measured during the ACT II experiment. Fig. 1 shows the geometry of the ACT II VLA, one of the measured sound speed profiles, the bottom profile derived in the area from Ref. 5, and the mode functions for the waveguide at 150 Hz. The sparseness

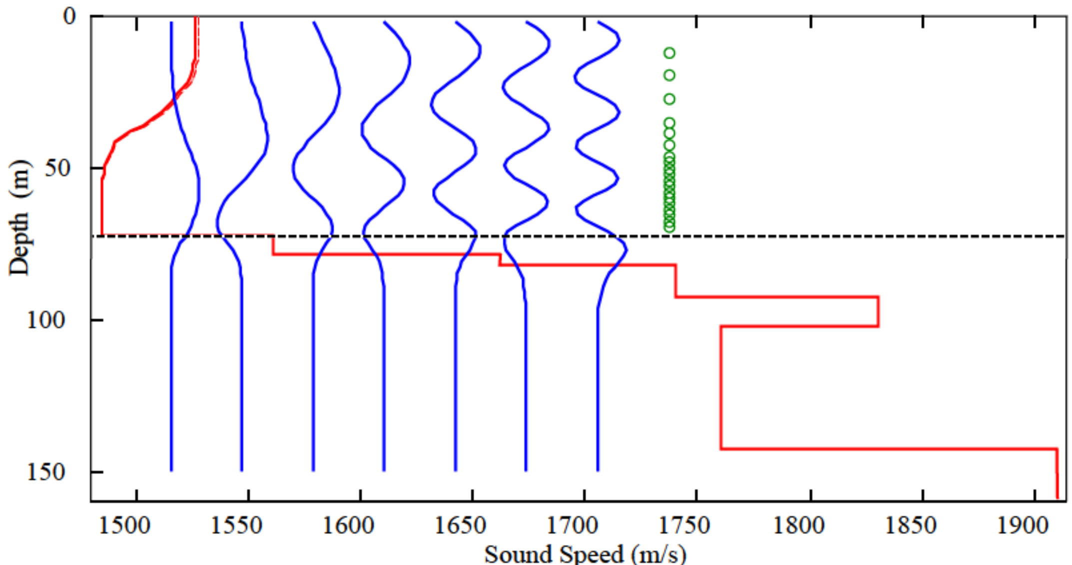

FIGURE 1. VLA elements (green circles), sound speed profile (red), nominal bottom profile[5] (red), and mode functions (blue) for the ACT II experiment.

of the VLA in the upper part of the water column is not ideal, but simulations indicated that low-order modes could be extracted fairly well.

Mode extraction from the ACT II data was performed for various range extents for six tones from 100–500 Hz. The mode extraction worked better for the lower frequencies (100, 150 and 200 Hz) because the SVD eigenvalues were well separated and because the SNR was high. Extracted modes at 150 Hz for range-independent and range-dependent legs of the TL2/93 run are shown in Fig. 2. Both

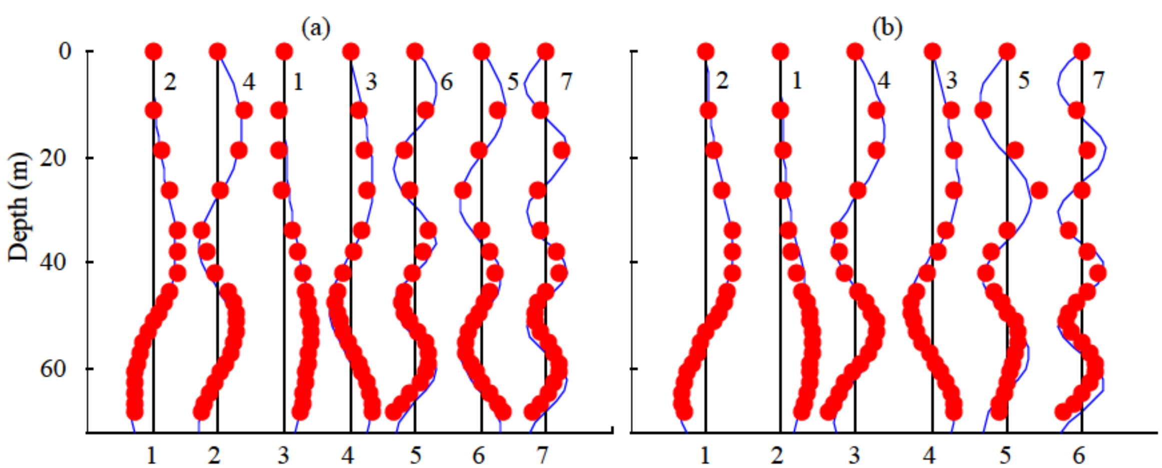

FIGURE 2. Extracted modes (circles) at 150 Hz from (a) a range-independent leg and (b) a range-dependent leg of the ACT II experiment using a range extent of 6–14 km. The continuous lines are modes modeled by ORCA for the nominal environment illustrated in Fig. 1.

extractions used range extents of 6–14 km. Despite the sparseness of the VLA, the mode extractions appear to have worked very well. The downward-refracting sound speed profile present during the measurements is reflected by the shapes of the extracted mode functions, particularly those of low order. The success of the range-*de*pendent mode extraction indicates that, if the range dependence is small enough, the adiabatic approximation holds, the mode shapes adapt themselves to the varying water depth, and the modes are extracted as they exist at the VLA.

Next, the extracted mode functions were used to invert for the geoacoustic parameters of the bottom. The bottom was assumed to consist of two layers and a lower halfspace; the parameters allowed to vary were the layer thicknesses, the compressional-wave sound speeds and attenuations and their gradients, and the layer densities. The results of the inversion procedure are summarized in Fig. 3. The sound speed at the top of the first sediment layer is close to that given in Refs. 5 and 6. The result for the water depth agrees well with the value of 71.6 m derived in Ref. 7. The extracted modes are not sensitive enough to density or to any parameters in the second layer to give reasonable estimates of those values.

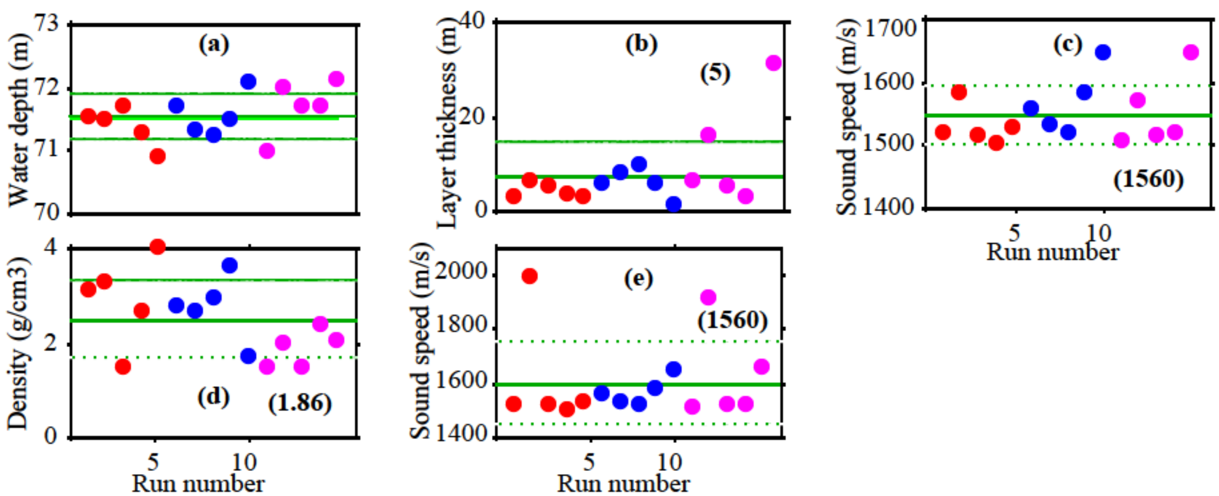

FIGURE 3. Inversion results using modes extracted at four frequencies from 200–500 Hz from a range-independent leg of the ACT II experiment. The three sets of colored dots indicate converged parameter values using sets of modes extracted from three different range extents. Within each color, five inversion runs were done using different starting environments. The mean value and standard deviation of each parameter for the 15 runs are also shown. The values reported in Ref. 5 are printed in bold.

In summary, theory and simulations indicate that the mode extraction technique should work well if the VLA samples the water column well, the source covers a sufficient range extent, and the SNR is good. The acoustic source need not be controlled: its depth, the phase of its tonals, and its precise track do not need to be known. When applied to the ACT II data set, the mode extraction appears to have worked very well, despite the relative sparseness of the array near the top of the water column. When the extracted modes were used to invert for the bottom, the results were encouraging, but the depth to which the parameter values could be reliably obtained was only 10 m or so. Since the mode functions decay rapidly with depth in the bottom, little information about the bottom below a few wavelengths is available. Although more information would be desirable, the field from sources beyond the near field is only dependent on the parameters near the surface. Unfortunately, the mode functions are not very sensitive to attenuation, even in the top sediment layer. The extracted depth-dependent mode functions are also useful for determining water depth and the sound speed profile in

the water column, but in practice these values can usually be measured by other means.

IMPACT/APPLICATIONS

This technique for geoacoustic inversion is applicable to vertical line arrays that span and sample the water column sufficiently well to account for the dominant modes of propagation. The source of acoustic energy must be quite loud and must traverse a sufficiently large range extent, but it does not have to be controlled, which makes it applicable to covert operations.

TRANSITIONS

No transitions have occurred for the geoacoustic inversion method. We continue to make the ORCA normal mode model available to the community and to provide support to users when needed. We have been informed of use of the model at the following institutions: NRaD, MPL; NAWC, U. of Hawaii; SACLANT; NRL SSC; U. of Victoria; MIT/WHOI; University of Bochum (Germany); and Pennsylvania State University. ORCA continues to be used as the “mode engine” for a the Range-Dependent Active (RDA) model, an adiabatic-mode modeling tool developed by ARL:UT to provide TL and active sonar predictions in real-world environments.

RELATED PROJECTS

None.

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PUBLICATIONS

E. K. Westwood and R. A. Koch, “Elimination of branch cuts from the normal mode solution using gradient halfspaces,” scheduled to appear in the October or November issue of *J. Acoust. Soc. Am.*